

Closed Loop Controlled Solar Cell Powered Embedded EZ-Source Inverter fed Induction Motor Drives

Nisha K.C.R.¹, T.N.Basavaraj²

¹Sathyabama University, Electrical & Electronics Department, Chennai, India

Email: nishashaji2007@gmail.com

²New Horizon College of Engineering, Electronics & Communication Department, Bangalore, India

Email: tnbasavaraj@yahoo.com

Abstract— This paper proposes the use of Embedded EZ-source inverter system (EZSI) as a single stage power conversion concept for adjustable speed drives (ASD) in photovoltaic applications. Open loop and closed loop control strategy of EZSI system are proposed. EZSI produces the same voltage gain as Z-source inverter (ZSI) but due to the DC sources embedded within the X- shaped impedance network, it has the added advantage of inherent source filtering capability and also reduced capacitor sizing. This is attained without any extra passive filters. By controlling the shoot-through duty ratio and modulation index, EZSI system can produce any desired AC output voltage even greater than DC rail voltage and it also provides ride-through capability under voltage sag. These advantages are more significant for adjustable speed drive (ASD) applications in order to regulate the speed. The operational analysis, control strategy and simulation results exemplify that an EZSI is the most promising technique for renewable energy applications in order to reduce the overall system complexity and thereby improving the inverter efficiency.

Index Terms—Adjustable Speed Drives, EZ-source inverter, harmonics, Shoot- through, Z-source inverter

I. INTRODUCTION

Nowadays, renewable energy applications are on greater demands, more particularly solar cell. A key component of PV generating system is the grid connected inverter. The transformer-less inverter topologies can be classified into two categories: two stage inverter topologies and single stage inverter topologies [1]-[4]. System performance depends on local climate, the orientation and inclination of PV array and inverter performance. The traditional photo electric systems contain VSI and CSI. They are either buck or boost, but not buck-boost converter. The common problem of this topology is that their main circuits cannot be interchangeable and also shoot through will occur when any two switches of the same phase leg is turned on which is a major killer to converter's reliability. To reduce the cost and to increase the system reliability Z-source inverter as a single-stage transformer-less inverter topology is first proposed [5].

By utilizing the unique LC network, a shoot-through zero state can be added to replace the traditional zero state of the inverter and to achieve the output voltage boost function. Henceforth, Z-source inverter provides a feasible single stage power conversion concept suitable for secondary energy

source such as photo electric system as they usually produce low variable DC voltage. Since its proposal, developments related to Z-source inverters have been taking place in various directions, covering its modulation [6]-[8], modeling [9]-[10], control [11]-[13] and other topological inventions [14]-[16]. But unfortunately, a closer view at the existing network would reveal that it causes chopping current to be drawn from the source, if no explicit hardware filter is added. This chopping current not only raises the semiconductor current rating, but also complicates the maximum power point tracking (MPPT) objective set for most renewable energy sources [17]. In view, a new class of Z-source topologies, named as the embedded EZ-source inverters, was proposed in [17]-[19], which however mainly focused on design of voltage and current type EZSI. The above literature does not deal with feedback control methodology for photovoltaic systems. This work plans to design, model and simulate open loop and closed loop controlled EZSI fed induction motor powered by solar electric system with implicit source filtering and reduced capacitor sizing.

II. OPERATING PRINCIPLE OF EMBEDDED EZ-SOURCE INVERTER

Two level voltage-type Embedded EZ-source inverter fed induction motor is shown in Fig. 1.

It has its DC sources embedded within the X-shaped impedance network, for filtering the currents drawn from the two DC sources of $V_{dc}/2$. Though the arrangement can occasionally interpret to a slightly higher cost, but the advantages exhibited by the EZ- source inverter outweigh the serious limitations [17]. These advantages are more clearly illustrated by analyzing the inverter operating principle. Based on switching states of the inverter, the EZSI can be classified into three operational states.

A. Operating States of the EZ-source Network:

Active State: Inverter bridge is operating in one of six active states. In this mode the front-end diode D_s is forward biased and the Inverter bridge and external load is replaced by a current source I_o as shown in Fig. 2(a). The capacitor is charged and energy flows to the load through the inductor. The inductor discharges in this mode.

Open State: Inverter bridge is operating in any one of the two zero states as the inverter short circuits the load through either upper or lower three switching devices. The bridge can be viewed as an open circuit shown in Fig. 2(b). The

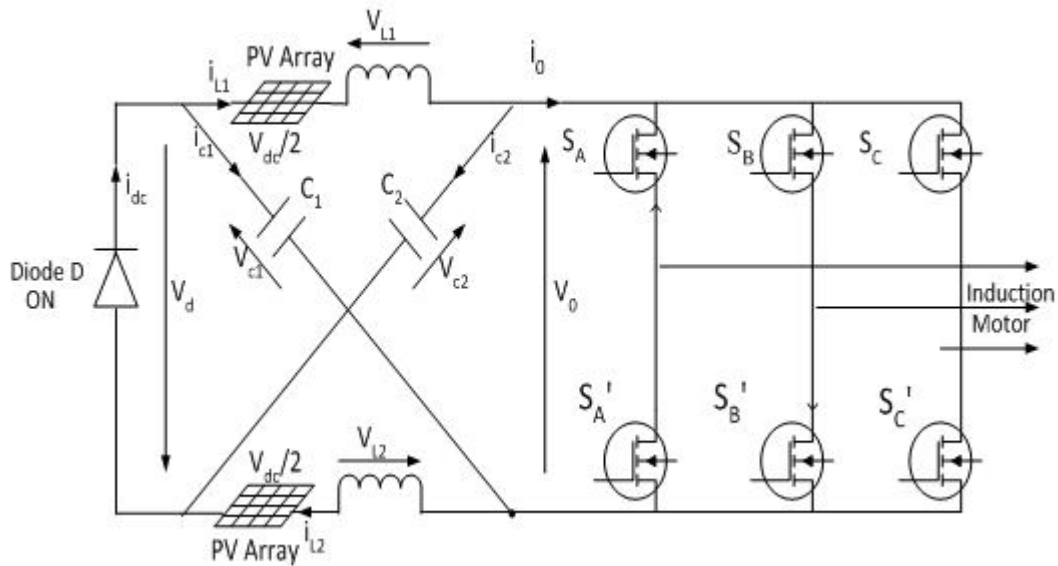


Fig. 1 Embedded EZ-source Inverter Circuit

voltage of DC source appears across the inductor and capacitor but no current flows to the load from DC source.

Shoot-through State: The inverter is in one of the seven different ways of shoot through and the bridge is viewed as short circuit from the DC link of the inverter as shown in Fig. 2(c). In this mode no voltage appears across the load like in zero state operation, but the DC voltage of capacitor is boosted to required value based on shoot through duty ratio.

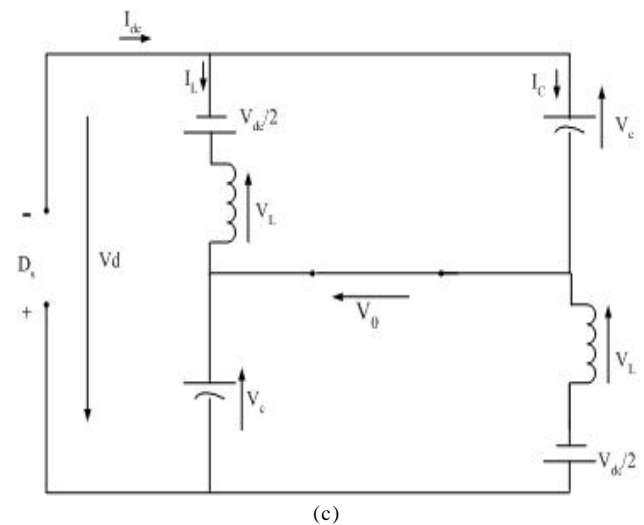
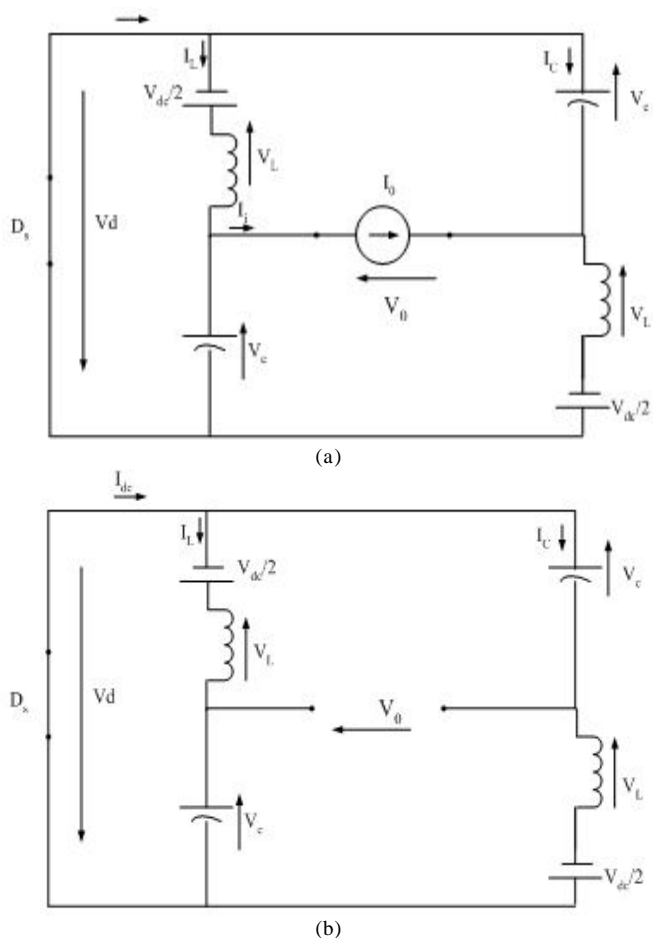


Fig. 2 Equivalent circuits a)Active state b)Null state c)Shoot through state

B. Circuit Analysis

Assuming that the inductors L_1 , L_2 and capacitors C_1 , C_2 have the same inductance (L) and capacitance (C) respectively, the E-Z-source network becomes symmetrical.

$$V_{L1} = V_{L2} = V_L; V_{C1} = V_{C2} = V_C \quad (1)$$

Active State ($S_x = S_x, x = A, B \text{ or } C; D_s = ON; \text{ time interval: } T_1$)

$$V_L = \frac{V_{dc}}{2} - V_C; V_d = 0; V_0 = V_C - V_L + \frac{V_{dc}}{2} = 2V_C \quad (2)$$

$$I_{dc} = I_L + I_C; I_0 = I_L - I_C; I_{dc} \neq 0 \quad (3)$$

Open State ($S_x = S_x, x = A, B \text{ or } C; D_s = ON$)

$$V_L = \frac{V_{dc}}{2} - V_C; V_d = 0; V_{dc} = 2V_C \quad (4)$$

$$I_0 = 0; I_L = I_C = \frac{I_{dc}}{2} \quad (5)$$

Shoot-Through State ($S_x = S_{x'} = ON$, $x = A, B$ or C ; $D_s = OFF$; time interval: T_0)

$$V_L = \frac{V_{dc}}{2} + V_C; V_0 = 0; V_d = -2V_C \quad (6)$$

$$I_L = -I_C; I_0 = I_L - I_C; I_{dc} = 0 \quad (7)$$

Averaging the inductor voltage over a switching period and equating it to zero, give rise to set of equations in terms of input voltage V_{dc} . The equations can be given as

$$\left\{ \begin{array}{l} V_C = \frac{V_{dc}/2}{1 - 2T_0/T} \\ \hat{V}_i = \frac{V_{dc}}{1 - 2T_0/T} = BV_{dc} \\ \hat{V}_{AC} = \frac{MV_{dc}}{2((1 - 2T_0/T))} = B\left(\frac{MV_{dc}}{2}\right) \end{array} \right\} \quad (8)$$

where V_C is the capacitor voltage, \hat{V}_i is the peak DC link

Voltage, \hat{V}_{AC} is the peak AC output voltage, M is the modulation index ($M \leq 1$) and B is the boost factor ($B \geq 1$).

Analysis clearly shows that EZ-source inverter system produces same transfer gain as Z-source inverter system even though EZSI has two DC sources embedded within the impedance network for achieving source filtering. Also the capacitor voltage in (8) is greatly reduced when compared to Z-source inverter inferring that there is a significant reduction of capacitor voltage ratings.

III. EMBEDDED Z-SOURCE NETWORK DESIGN

To realize the operation of EZSI, a design calculation has been provided. Assuming that the input voltage is $V_{dc}=110V$, $B=3.8$, $R=1\Omega$, $\Delta I=0.4A$; $\delta=T_0/T$.

$$B = \frac{1}{1 - 2\delta} \Rightarrow \delta = 0.368 \quad (9)$$

A. Inductor Design

During VSI mode (traditional four states) operation the input voltage appears across the capacitor and only pure dc current flows across the inductor. During shoot through mode, the inductor current increases linearly and the inductor voltage is same as that of capacitor voltage ($V_L = V_C = V$). But during non-shoot through mode the inductor current decreases linearly and the voltage across the inductor is the difference between the input voltage and capacitor voltage [20]. The average current through the inductor is

$$\bar{I}_L = \frac{P}{V_{dc}} \quad (10)$$

The Inductor value can be given as:

$$L = \frac{V_{dc} * \delta}{f * \Delta I} = 10mH \quad (11)$$

Where ΔI =Inductor maximum current-Inductor minimum current (60% peak-peak current ripple is chosen) and is assumed as 0.4.

B. Capacitor Design

The capacitor value can be calculated using the formula

$$C = \frac{\delta}{2fR} = 18\mu F \quad (12)$$

C. Peak DC link voltage

$$\hat{V}_i = 3.8 * V_{dc} = 418 V \quad (13)$$

D. Capacitor voltage

$$V_{C1} = V_{C2} = 3.78 * \frac{V_{dc}}{2} = 208 V \quad (14)$$

E. The output phase voltage from the inverter

$$\hat{V}_{AC} = 3.42 * \frac{V_{dc}}{2} = 188.1V \quad (15)$$

IV. SIMULATION RESULTS

To assess the operational and performance analysis of the solar cell powered EZSI fed induction motor, simulation model has been established using Matlab/Simulink package. The simulation is done up with the following parameters: $L_1=L_2=10mH$; $C_1=C_2=18\mu F$; and the purpose of the system is to control a 3-phase induction motor powered by solar cell in various conditions.

A. Three phase EZSI without disturbance:

Open loop control of three phase EZSI induction motor drive system is shown in Fig. 3. Pulses for switches with inserted shoot-through are shown in Fig. 4. Solar output voltage of $V_{dc}/2=55V$, Line voltage and current waveforms in boost mode with $T_0/T=0.368$ are shown in Fig. 5 The spikes in the output voltage are due to the PWM switching pulses. The currents are smoothened by the inductance of the machine. Therefore the current harmonics are reduced. Capacitor voltages of $V_{C1}=V_{C2}=208V$ is shown in Fig. 6 and the capacitor voltages are greatly reduced than their counterparts. The rotor speed increases and the rotor settle down at 1500 rpm and is shown in Fig. 7.

B. Open loop model of three phase EZSI with disturbance

The open loop control of three phase EZSI with disturbance is shown in Fig. 8. At the input side a disturbance of 15% is given after a time period of 1 second as shown in Fig. 9. Speed disturbance and torque variation is shown in

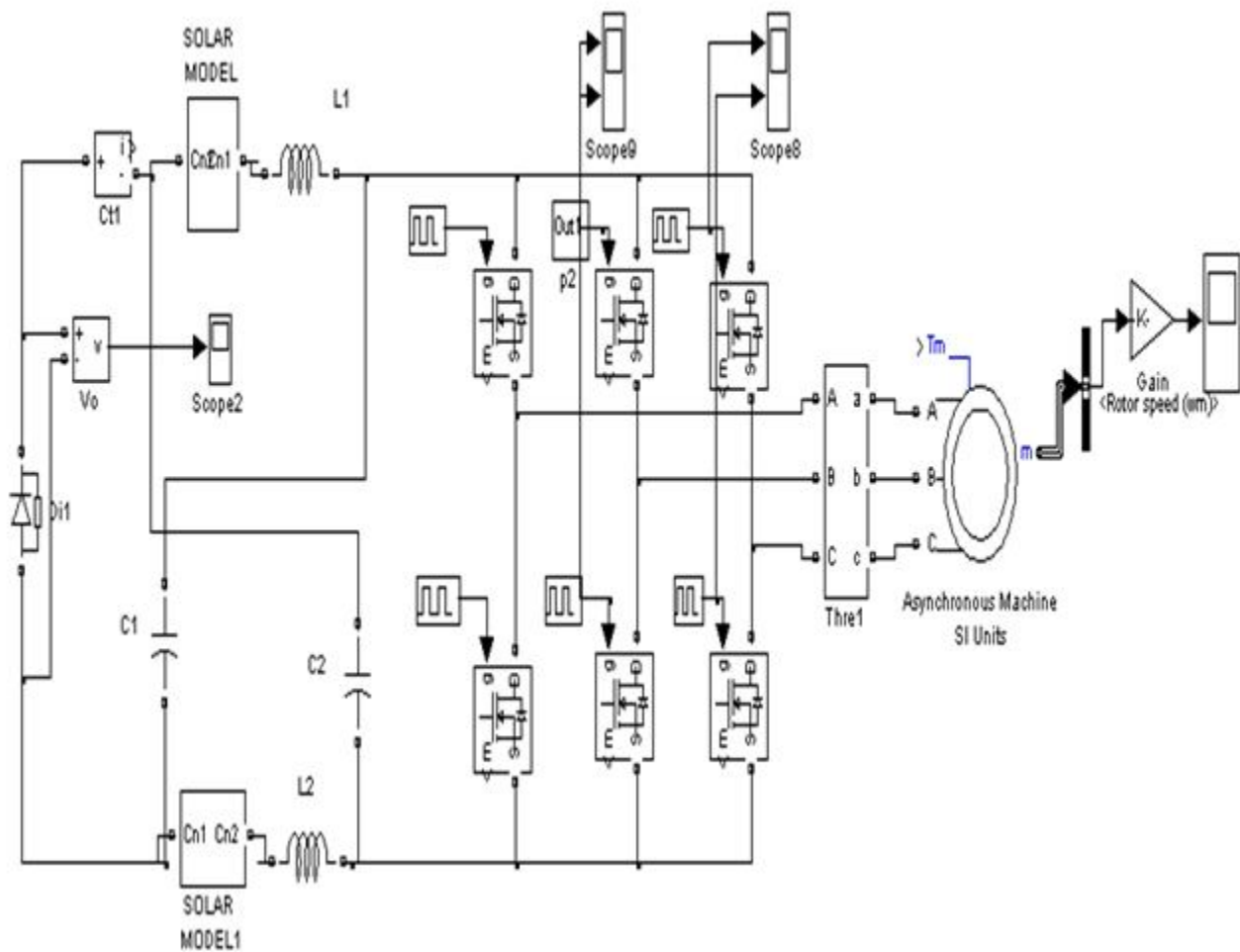


Fig. 3 Three phase EZSI fed induction motor drive system without disturbance

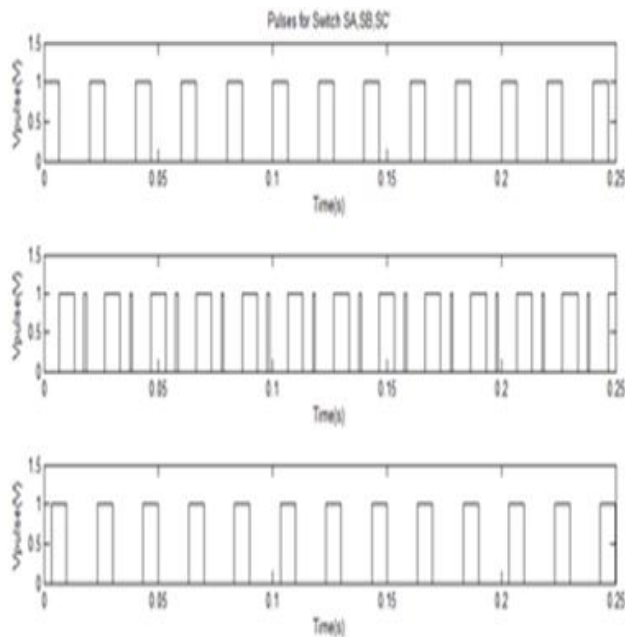
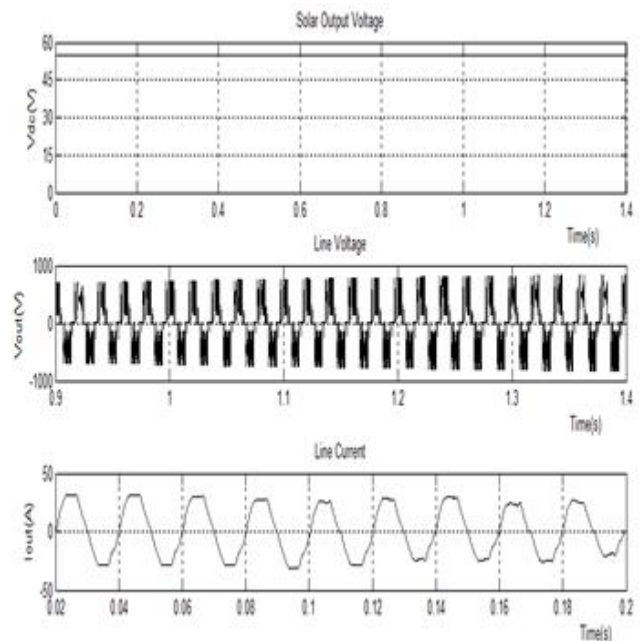
Fig. 4 Pulses for Switches S_A, S_B, S_C .

Fig. 5 Line Voltage waveforms

Fig. 10. The speed of the motor increases due to the step rise in the input voltage. The output voltage and current waveforms are shown in Fig. 11.

C. Closed loop model of three phase EZSI system:

Circuit model of closed loop controlled EZSI fed induction motor drive system is shown in Fig. 12. The output AC voltage

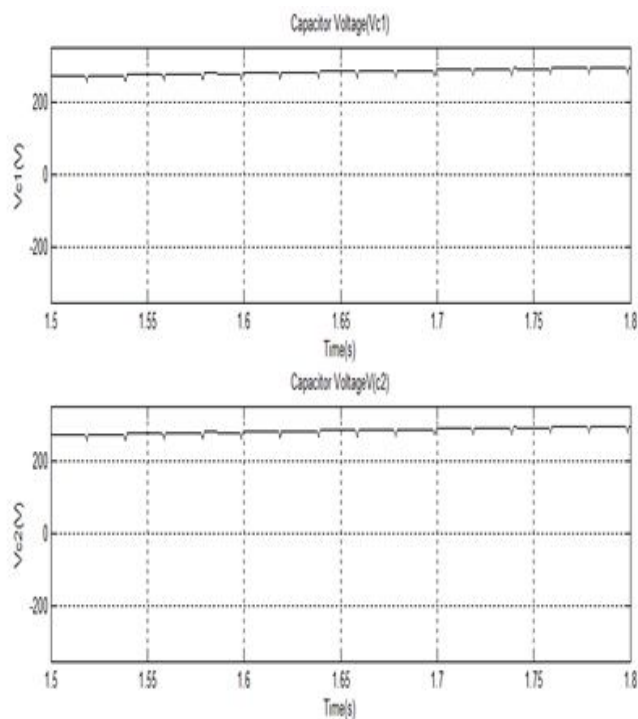


Fig. 6 Capacitor Voltages

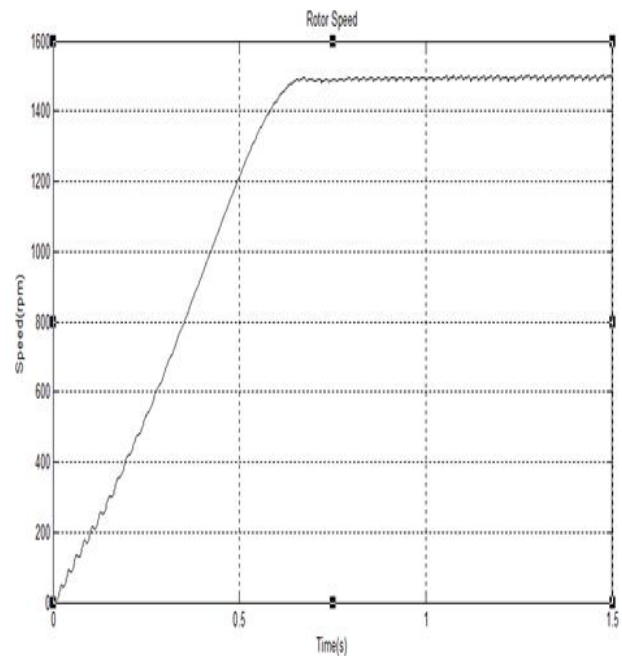


Fig. 7 Speed response of the system

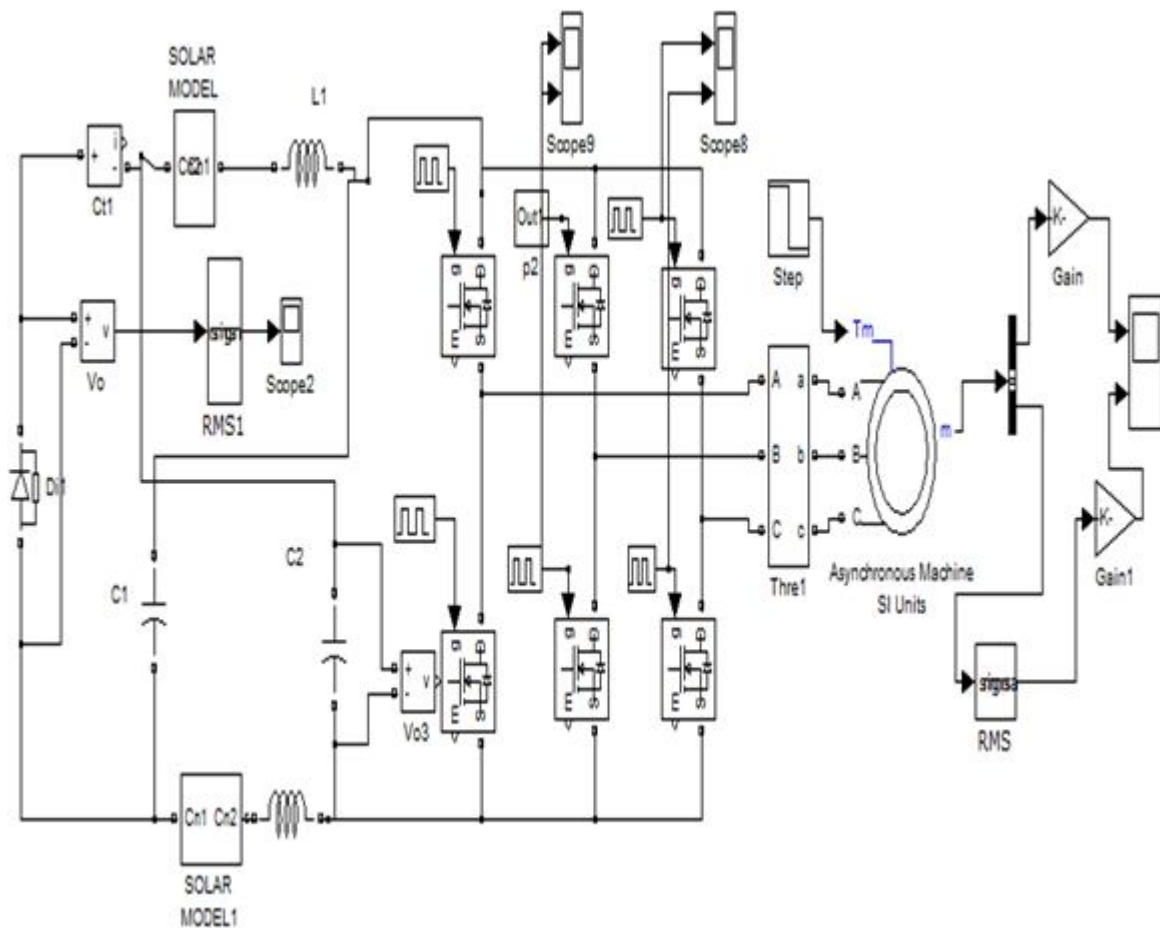


Fig. 8. Open Loop model of EZSI fed induction motor drive system with disturbance

is sensed and compared with reference voltage. The error generated is given to the PI controller in order to regulate the output voltage with respect to the change in the input voltage.

The speed response of the closed loop system is shown in Fig. 13. It can be seen that the speed of the motor increases and then reduces to the set value. The speed variation is

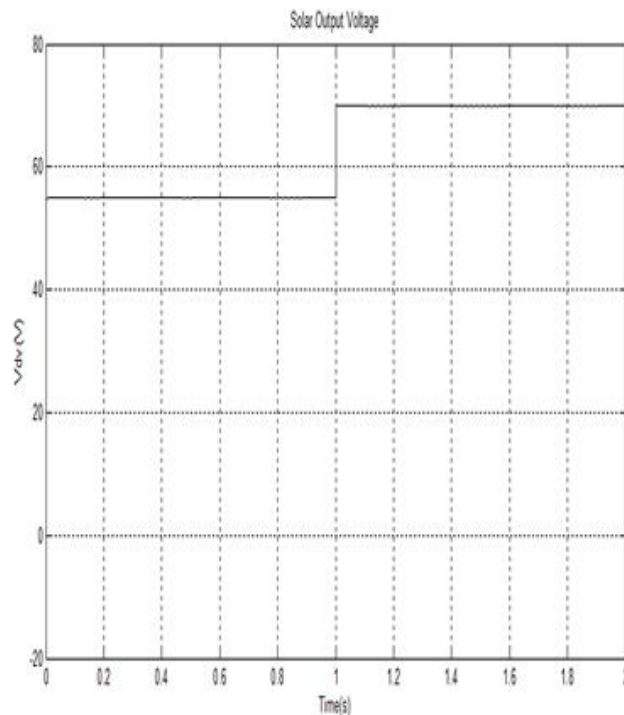


Fig. 9. Solar output Voltage

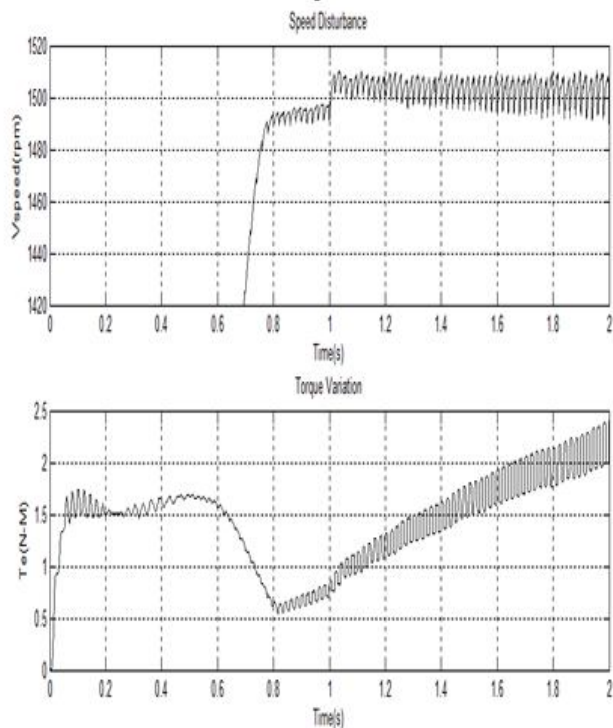
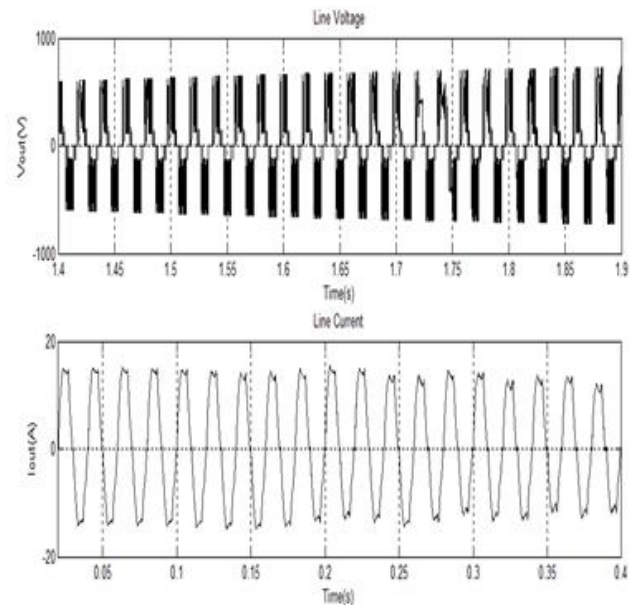


Fig. 10 Speed disturbance and Torque variation shown in Fig. 14. Line voltage and current waveforms are shown in Figs. 15 & 16 respectively. Thus the closed loop system is able to regulate the speed.

V. CONCLUSION

In this paper, closed loop control of EZ-source inverter fed induction motor for photovoltaic application is proposed. EZ-source operating states, circuit equations, inductor and

Fig. 11 Line voltage and Current waveforms with $T_q/T=0.368$

capacitor design are provided. The novel idea of this work is to model a closed loop control strategy for 3-phase induction motor using embedded EZ-source concept. Simulation results using Simulink are shown to verify the theoretical results. The design result provides accurate DC-link EZ-source network parameters. Analysis shows that EZ-source inverter produces the same voltage gain as their traditional Z-source inverter with significant reduction in capacitor sizing. The additional advantages like lower voltage/ current stresses and implicit source filtering are gained without requiring extra hardware. It is seen that small ratings of passive components are adequate to compensate the unpredictable solar input; thereby efficiency mitigation of induction motor can be avoided. The inverter is able to override the DC voltage sags. So EZ-source inverter system is a competitive secondary that can be used for solar energy harnessing applications where implicit source filtering is critical. The disadvantage of EZ-source inverter system is that, it requires two DC sources. Simulation results have also confirmed that the closed loop controlled EZ-source inverter system can regulate the speed with improved harmonic performance than their counterparts.

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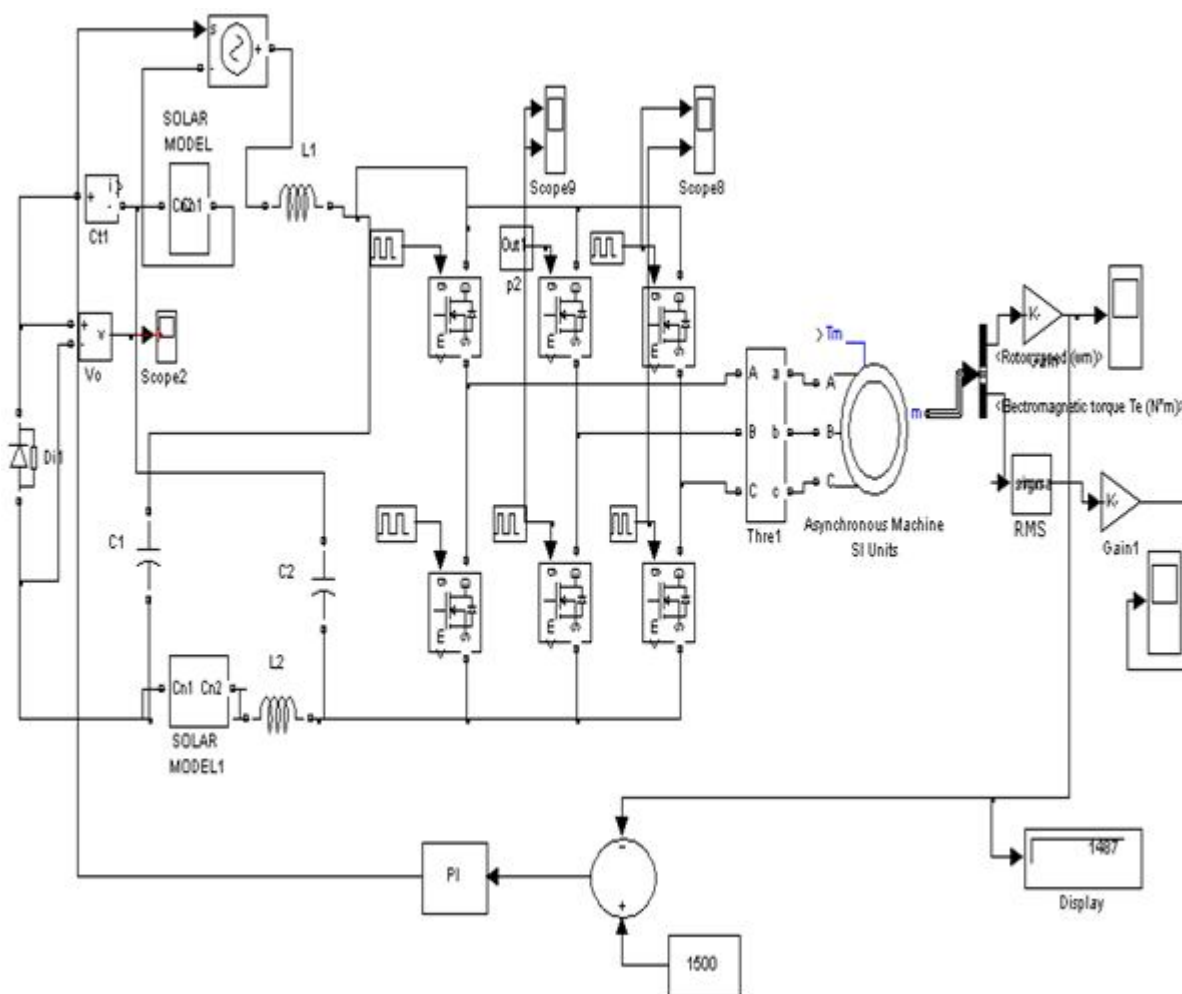


Fig. 12. Closed Loop model of three phase EZSI fed Induction motor drive system

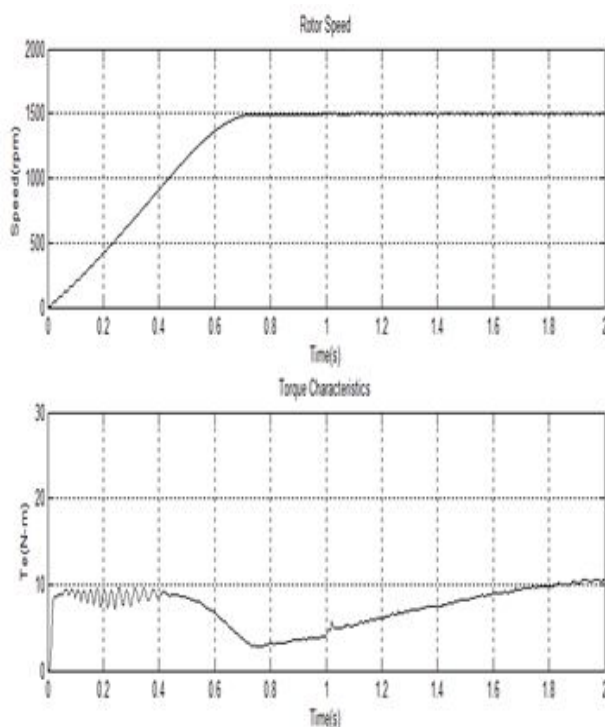


Fig. 13. Speed response of EZSI system

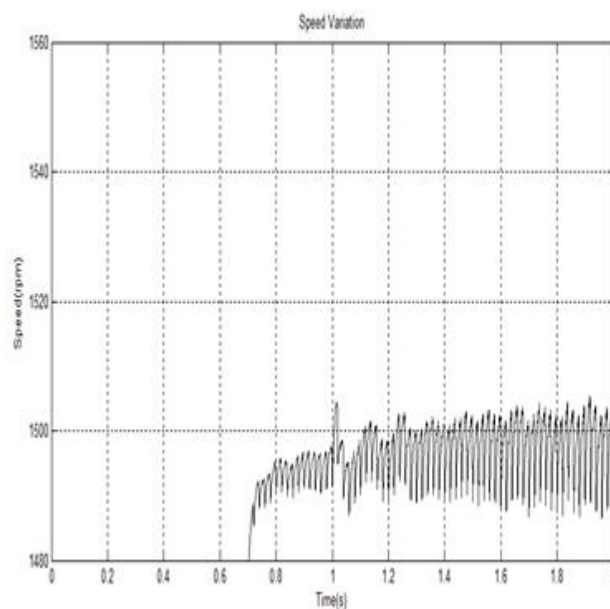


Fig. 14. Speed Variation

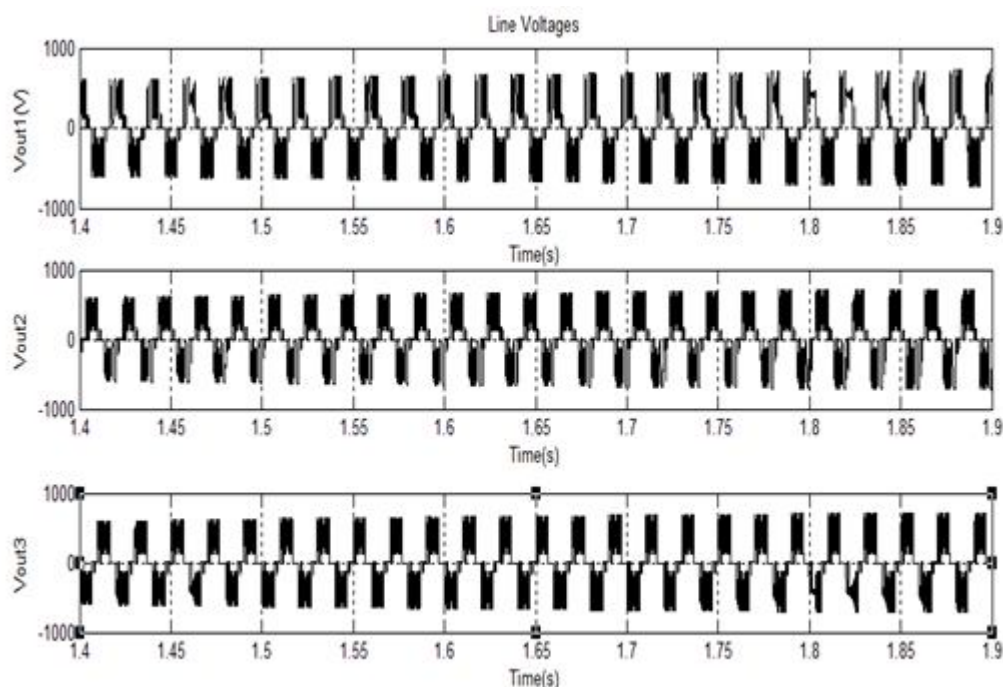


Fig. 15. Line Voltage Waveform

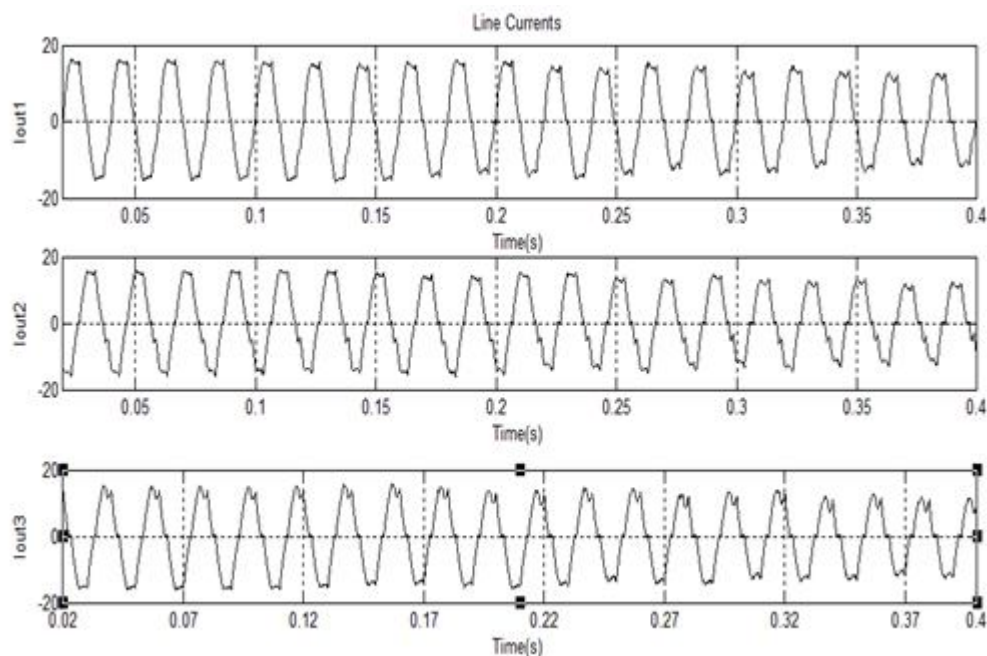


Fig. 16. Line Current Waveform

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